NASA TT F-10,185

NASA TT F-10,185

HEAT TREATMENT OF TUNGSTEN BULBS

B. Jesionek and A. Kostkowski

Translation of "Obróbka cieplna żarników wolframowych". Rudy i Metale Nieżelazne, Vol.10, No.2, pp.59-65, 1965.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON JUNE 1966

NASA TT F-10,185

HEAT TREATMENT OF TUNGSTEN BULBS

*[/59]

B. Jesionek and A. Kostkowski

Technological investigations established that the best filaments made of grade GK ZML tungsten wire are obtained with the use of the following heat-treatment parameters: I. Annealing at 1100°C and II. two-step annealing, with the first step at 1200°C for 10 min and the second step at 1400°C for 5 min. Metallographic investigations established that an increase in resistance to sagging and warping can be obtained by proper stress relief anneal of the filaments and by a uniform and rapid recrystallization process.

INTRODUCTION

2 4727

The present investigation had the purpose of establishing the optimal parameters of heat treatment for bulbs (filaments) of tungsten wire intended for the general series of light bulbs (25, 40, 60, and 100 w/220 v) which would ensure good mechanical properties of the filaments prior to mounting into the bulb as well as minimum deformation (sagging and warping) during the lifetime of the bulb. The investigation was carried out on GK grade of tungsten wire produced by the Zaklady Materialów Lampowych im. J. Grimau. A simultaneous objective was to establish a correlation between the recrystallization process and the character of the final wire structure after recrystallization, and to define the operating properties of the filaments.

Author

* Numbers in the margin indicate pagination in the original foreign text.

Recrystallization of Tungsten Wire and Effect of Resultant Phenomena on the Operating Properties of the Filament

The recrystallization of pure (untreated) tungsten wire does not differ fundamentally in nature from the general recrystallization scheme of most metals. In view of the small diameter of the wire, the crystals formed as a result of secondary recrystallization occupy its entire cross section; the grain boundaries, in accordance with the principle of minimum surface energy, are perpendicular to the surface and hence to the wire axis. Such a final structure is disadvantageous in many respects. On heating the wire by AC current, the crystals with boundaries normal and perpendicular to the wire axis exhibit a tendency to reciprocal displacement along the grain boundaries (so-called "offsetting"), producing a steplike effect in the wire. During operation of the bulb, the wire with grain boundaries normal and perpendicular to the wire axis is prone to sagging, i.e., elongation under its own weight, assuming the form of garlands whose size depends on the distance between the holders. It can be assumed that this is due to the viscous flow of the material along the grain boundaries. Some authors distinguish between primary sagging which occurs in the first few seconds of lighting the bulb, secondary sagging which appears after the next 10 - 20 min of burning, and final sagging which occurs during protracted burning of the bulb (Bibl.1).

The very low recrystallization point of pure tungsten does not permit adequate heat treatment of the filament prior to mounting into the bulb, in view of the brittleness of tungsten in the recrystallization state (tungsten exhibits a markedly lower resistance to rupture along the grain boundaries than throughout the crystals).

To forestall the occurrence of the above-mentioned phenomena, small quanti-

ties of additives are added to the tungsten oxide prior to reduction. For the GK grade, these are about 0.03% Al_2O_3, 0.4% SiO_2 and about 0.2% K_2O. A considerable portion of these additives evaporates during the baking and subsequent plasticization, so that their content in the finished wire is already greatly reduced. These additives, which change the equilibrium conditions of the final structure after recrystallization, give the grain boundaries an unstable, /60
i.e., serrated, form with the grain boundaries inclined at a small angle to the wire axis, and raise the recrystallization temperature of the tungsten. Some investigators (Bibl.4) assume that these admixtures or their decomposition products form insoluble intermetallic phases with the tungsten, while others are of the opinion that they enter into solution (Bibl.3). On the basis of the character of the interaction of the admixtures, the hypothesis that they are partially soluble in the tungsten appears most probable. This is indicated both by the rise in recrystallization temperature as well as by the increase in the grain size following secondary recrystallization. The presence of the serrated grain boundaries after recrystallization speaks for the incomplete solution of the admixtures. According to investigations by Millner, Prohaška, and Horwath (Bibl.5), the growth rate G of the grains of tungsten wire, grade UC (prepared with the addition of K_2O and SiO_2) is the same as that for the grade GK, while the seeding rate N is about ten times greater in the case of UC, resulting in an average grain length about ten times that of GK. This is rather distinct evidence of the fact that the aluminum is in solution.

The recovery process for tungsten wire and the primary recrystallization follow a course similar to that of most other metals, while the course of secondary recrystallization depends largely on the grade of tungsten used (its composition). According to investigations by Davis (Bibl.2), once started, secondary recrystallization may proceed via two mechanisms:

1. formation of small equiaxial grains which then grow at the expense of one another;
2. immediate formation of large secondary grains, which grow at the expense of the primary recrystallized structure.

The first mechanism occurs in the case of pure tungsten and the second, in the case of GK. In the technique used at the Zaklady Wytwórcze Lamp Elektrycznych im. Róża Luksemburg, the heat treatment of the production-series single filament comprises the following operations:

a. transition annealing of the wire coil on its core in an atmosphere of protective gas (hydrogen and nitrogen at 1:3 ratio) at a temperature of 1100°C (this annealing will hereafter be referred to as "anneal I");
b. cutting of the filaments, together with the core, to the desired dimension;
c. removal of the core by chemical means;
d. annealing of the finished filaments in molybdenum containers at a temperature of 1150 - 1250°C for 10 min in an atmosphere of moist hydrogen (this annealing will be referred to as "anneal II").

After mounting into the bulb, the filaments are subjected to preliminary lighting with the aid of an automatic mounting machine by application of increasing voltage causing a gradual recrystallization of the wire.

A properly selected heat treatment must ensure the following: proper stress relief of the wire strengthened by cold-working during plasticization; resistance of the filaments to warping in burning; removal of graphite from the wire, which interacts with tungsten at high temperatures to form intermetallic phases leading to brittleness and deformation of the filament; and recrystallization of a type that will yield long crystals with a final structure of serrated boundaries not parallel to the wire axis. This in turn ensures resistance to sagging.

PROCEDURE

A number of variants of the heat treatment of the filaments were tested at various temperatures of anneal I and II and varying duration of anneal II. Modifications of the two-step annealing were also used. The effect of graphite coating of the wire was investigated in addition to the effect of the temperature and the anneal I scheme.

To establish the correlation between the operating properties of the filaments and the character of the recrystallization process, a number of microscopic tests were performed on the structure of filaments subjected to various heat treatments, following successive brief periods of burning for 0.25 to 3.5 sec. The burning in this case was instantaneous, using 220 v voltage, in order to enhance the conditions for the appearance of both sagging and warping. Control tests were run on filaments prepared by several outside processes, to compare them with the technique used by the ZWLE. Mainly, technologies developed for filaments wound on an iron core were tested; however, to eliminate the effect of the iron, control tests were made on molybdenum and steel cores in all cases. As indicated in the literature (Bibl.6, 10) and shown by our own experiments (Bibl.9), the effect of iron is often adverse. The sagging and warping were evaluated visually, by comparison with a standard. The appearance of the filaments was evaluated after burning with the aid of an automatic mounting machine and after short-time testing on an endurance test rig. The latter was carried out at 240 v for 40 hrs (corresponding to 40 hrs at 220 v).

To determine the character of the final structure of the filaments, we supplemented the microscopic examinations by tests to determine the average length of the crystals in the filaments. The number of crystals was counted under the

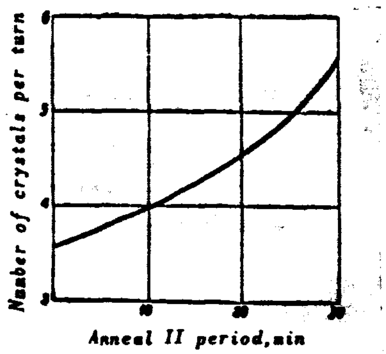

Fig.1 Plot of Average Length of Crystals in Filament vs. Duration of Anneal II

microscope at 100 × magnification, following digestion. Plots were obtained for the dependence of the average length of the crystal on the temperature and on the duration of anneal II. Each point on the graph represents an average of 10 filaments of a given variant. For a comparative determination of the average size of the crystals in the filament we used the length of the crystal rather than its area, since in such thin wires the crystals occupy the entire cross section of the wire.

The tests were carried out basically on filaments for 220/60-w bulbs (wire diameter = 0.030 mm); however, experiments with several other types of production-series filaments were made as check tests.

EXPERIMENTAL PART

Effect of Duration of Anneal II

The effect of the duration of anneal II was investigated at a constant temperature of 1200°C. Dried hydrogen was used as protective atmosphere. The anneal I was done at 1100°C in an atmosphere of nitrogen gas. Tests were carried out using annealing times of 2, 5, 10, 20, and 30 min. It was found that the anneal II periods used will not produce brittleness of the filaments following heat treatment, but that they exert a considerable effect both on the sagging and warping and on the recrystallization process of the wire. Whereas filaments annealed for 10 min can, following burning in the automatic mounting

Fig.2 Structure of Filament, with a Two-Minute Anneal II, after Burning for 0.8 sec. Magnification × 350

machine, still be considered of satisfactory quality (although they already exhibit a certain tendency toward sagging and warping), shorter periods of anneal II result in a gradual increase in sagging and warping. Anneal II of 20- and 30-minute duration almost completely eliminates deformations on burning. The durability test did not basically affect the evaluation of the effect of the individual anneal II periods and merely served to emphasize the differences between the individual variants. Testing of the filaments for the average crystal length showed that this length increases with increasing duration of anneal II

(Fig.1).

Metallographic investigations of the filament structure during burning /61 disclosed an increased uniformity of the recrystallization process with increasing anneal II period. Figure 2 shows, by way of example, the structure of a filament pre-annealed for 2 min after burning for 0.8 sec, while Figs.3 and 4 give the structure of filaments pre-annealed for 30 min after burning for 0.25 and 0.4 sec, respectively.

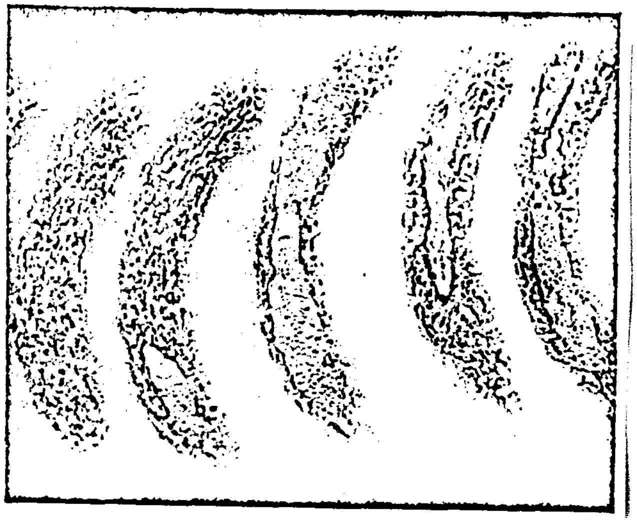

Fig.3 Structure of Filament, with a 30-Minute Anneal II, after Burning for 0.25 sec. Magnification × 350

Effect of Anneal II Temperature

The experiments were carried out at anneal II temperatures of 800, 1000, 1200, 1400, and 1600°C (for 10 min in an atmosphere of dried hydrogen). In addition, tests were run on a variant with two-step annealing (first step at 1100°C for 10 min, second step at 1600°C for 5 min) and on a variant in which anneal II was omitted. Anneal I was carried out under technological conditions.

None of the employed temperatures caused brittleness of the filaments following heat treatment, but a considerable effect of the temperature was noted on the dimensional stability of the bulb filament. Both excessively low (below 1000°C) and excessively high (above 1400°C) anneal II temperatures increase the

Fig.4 Structure of Filament, with a 30-Minute Anneal II, after Burning for 0.4 sec. Magnification × 350

susceptibility of the filaments to sagging and warping. Filaments for which the anneal II was omitted showed the most extensive deformation, while those with two-step annealing proved most stable, exhibiting even somewhat better properties than those annealed for 30 min at 1200°C. Prolonged burning in the test frame again only accentuated the differences between the individual variants. Raising the anneal II temperature above 1400°C as well as lowering it has an influence on the gradual reduction in grains (Fig.5). The longest crystals, however, were obtained in samples subjected to two-step annealing (5.46 crystals per turn).

It was found that secondary recrystallization in filaments fabricated without the anneal II sets in considerably later, with the secondary grains beginning to form only after three seconds. It was noted, at the same time, that considerable warping of the filaments appears much earlier, prior to the onset of secondary recrystallization. Manifestations of primary recrystallization appear already for the shortest burning periods, with the recrystallization exhibiting nonuniform behavior. Examples of the recrystallization process in such filaments are given in Figs.6 and 7. The final structure of the filaments fabricated without the anneal II is characterized by highly nonuniform and minute

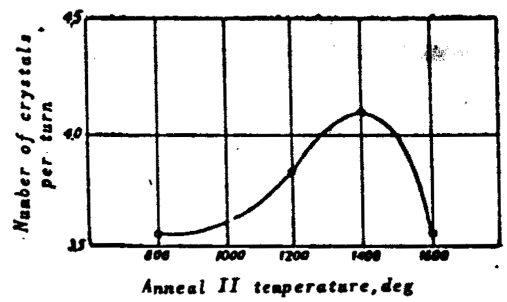

Fig.5 Plot of Average Length of Crystal in the Filament vs. Anneal II Temperature

grains. The recrystallization process in filaments with low anneal II temperatures resembles the recrystallization process in filaments with short anneal II periods. When annealed at temperatures above 1400°C, secondary recrystallization sets in rapidly and ends rapidly (after about 1.5 sec). The process is highly irregular, and the final structure is heterogeneous with a large amount of minute grains.

Secondary recrystallization in filaments where two-step anneal II was used runs a very rapid and uniform course (the process is complete already after 0.8 sec). The final structure is characterized by long grains with serrated edges.

Effect of Temperature and Anneal I Scheme (Combined with Effect of Graphite Wire Coating)

The effect of the temperature and anneal I scheme was investigated together with the effect of graphite coating of the wire, for which purpose graphite wire was employed. The tests were made with anneal II temperatures of 800, 1000, 1100, 1300, and 1400°C. In addition, a two-step (first step at 1100°, second at 1400°C) annealing variant was tested. The anneal II was done at a temperature of 1200°C for 10 min in an atmosphere of dried hydrogen. The anneal I was carried out in an atmosphere of non-dried hydrogen.

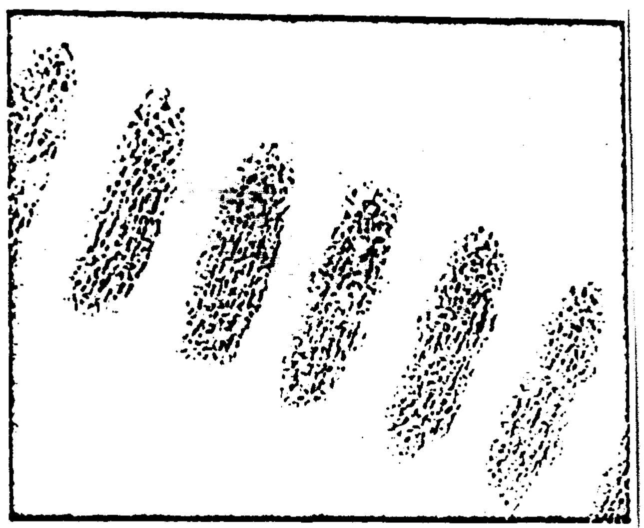

Fig.6 Structure of Filament Fabricated without Anneal II, after Burning for 2.5 sec. Magnification × 350

The highest resistance to warping and primary sagging (after burn tests /62 in the automatic mounting machine) was exhibited by the filaments with the two-step anneal I. However, following protracted burning (40 hrs at 240 v) they exhibited considerable flexure and thus a lack of resistance to final sagging. Check tests of the average crystal length for these filaments yielded 5.2 crystals per turn.

Sufficiently good filaments were obtained with the anneal I at 1100°C. Reducing the temperature to below 1000°C mainly leads to warping of the filaments, while raising the temperature to above 1100°C produces considerable sag.

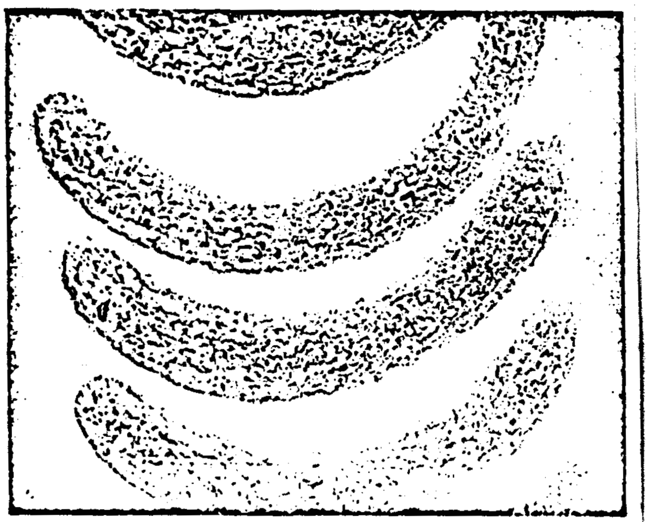

Fig.7 Structure of Filament Fabricated without Anneal II, after Burning for 2.5 sec. Magnification × 350

No brittle filaments following heat treatment were observed in any of the variants. Bulbs made with filaments annealed at 1300° and 1400°C showed a lower endurance limit, with about one-third burning out before the 40-hour test of operating at 240 v. Recrystallization of the filaments, when using the two-step annealing, sets in with a marked delay. After 1.5 sec of burning, the filament structure is still nearly fibrous (Fig.9). Both primary and secondary recrystallization proceed uniformly and rapidly. There is a gradual coarsening of the primary grains, followed by the formation of secondary grains which rapidly take up the entire cross section of the wire and continue to grow along its axis at the cost of the primary recrystallized structure (Figs.10a-c). The final structure is characterized by long crystals, but the grain boundaries tend to straight lines and perpendicularity to the wire axis (Fig.11). The final structure of filaments annealed at high temperatures is characterized by great inhomogeneity of grain size, with a predominance of fine grains. Both primary and secondary recrystallization occur rapidly and irregularly. In annealing at too low a temperature (below 1000°C), recrystallization also proceeds rapidly and nonuniformly, but the effect of lowering the temperature is less than that of raising it.

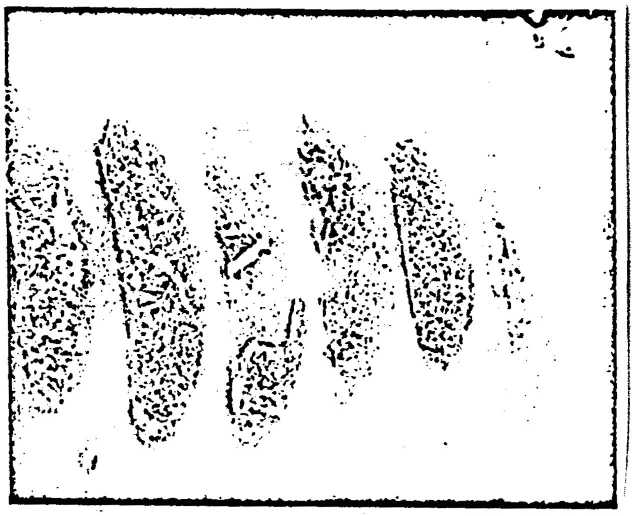

Fig.8 Structure of Filament with Two-Step Anneal II, after 0.8 sec Burning. Magnification × 350

Investigation of other Heat-Treatment Techniques in Production-Series Filaments with the GK Wire of Zakl. Mat. Lamp. Grimau /63

A comparison of the effectiveness of heat-treatment processes of other countries with those used at the ZWLE Róża Luksemburg was conducted on the basis of obtainable information of the technology used for steel cores in the Philips Works, Berliner Glühlampenwerk, and the Swedish firm "Lumalampan" in Stockholm. The tests were carried out for the variants presented in Table 1.

It was found that, subsequent to a preliminary test burn in the automatic mounting machine, the greatest stability was exhibited by the filaments of the variant No.45 (BGW technology). Highly stable filaments were obtained also for the variants Nos.41 and 42 (Luma), and slightly less stable but still satisfactory for the variants Nos.40 and 46 (ZWLE). On the other hand, filaments made in accordance with the Philips technology (variants Nos.43 and 44) were marked by an extensive tendency to sagging and warping. Burning of the filaments for 40 hours at 220 v affected only insignificantly the differences between the variants, except for the fact that the filaments of the variant No.45

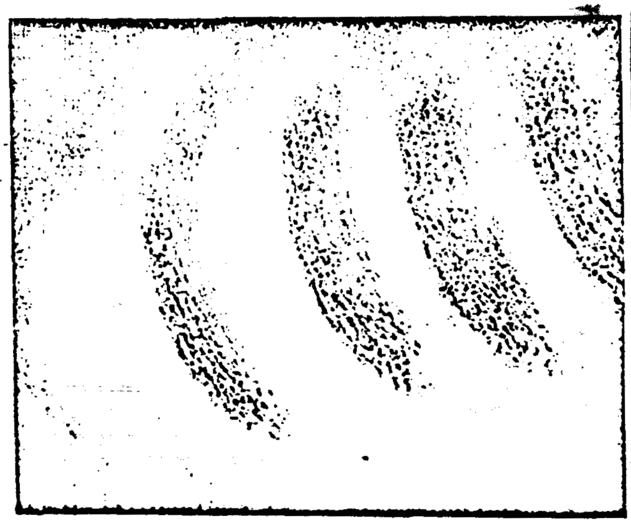

Fig.9 Structure of Filament with Two-Step Anneal I, after Burning for 1.5 sec. Magnification × 350

had a distinct tendency to sagging. It was found that filaments of the BGW variants possessed the longest crystal, followed in sequence by Luma, ZWLE, and Philips (Table 2). Summarizing the conducted tests, it can be stated that the best results for production-series bulb filaments made of GK ZML wire are obtained with the process used by the "Lumalampan" firm of Stockholm, followed by ZWLE, BGW, and Philips.

Discussion of the Results

It was determined in the investigations that the increase in resistance of

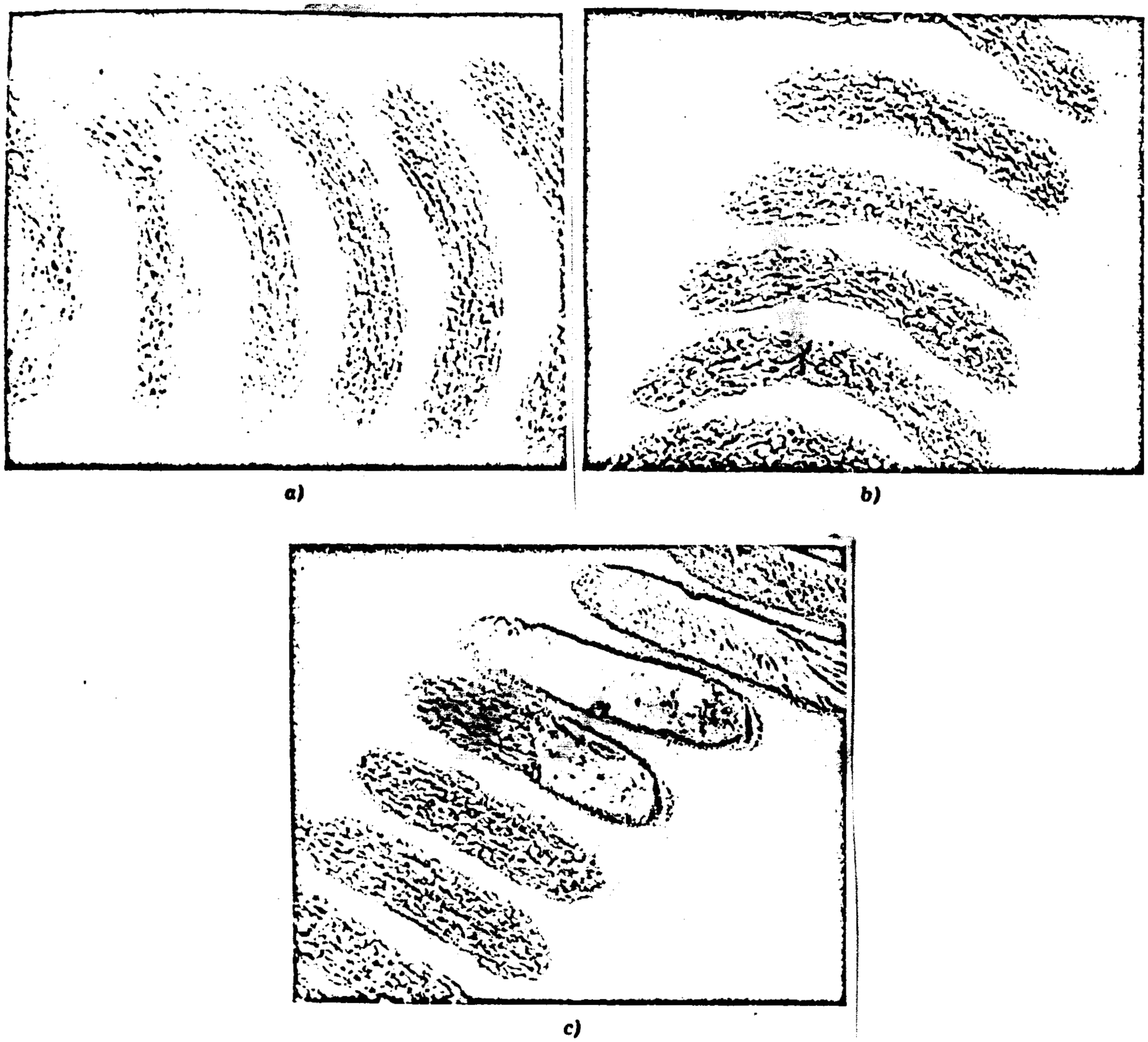

Fig.10a, b, and c Structures of Filament with Two-Step Anneal I, after Burning for 2.5 sec. Magnification × 350

various filaments to sagging and warping is due to the formation in the filaments after recrystallization of a structure characterized by long and uniform grain with boundaries that are serrated and inclined to the wire axis through an angle other than 90°, as well as to proper stress relief of the wire. Formation of the above-described structure is dependent on a uniform and rapid recrystallization process, which is largely governed by application of the proper heat treatment prior to mounting of the filaments in the bulb.

From the viewpoint of the dislocation theory, recrystallization can be conceived as a process of displacement and elimination of dislocations, and is therefore dependent on the rate of elimination of the dislocations in the plastically reworked material. Impurity atoms in the solid solution, distributed

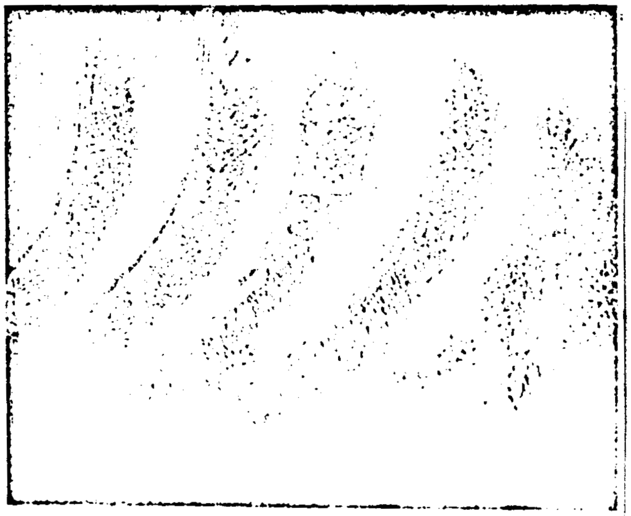

Fig.11 Structure of Filament with Two-Step Anneal I, after Burning for 40 Hours at 240 v. Magnification × 350

around the dislocation in the form of a cloud, block the dislocation motion and hamper the recrystallization process. On the other hand, the presence of foreign discrete phases in the base material influences the increased rate of seeding (N) and the decreased rate of grain growth (G), leading to a decrease in grain size. The presence of such phases also contributes to the lowering of the recrystallization temperature and the formation of grains with complex configuration of the boundaries. /64

It can be supposed that, following dissociation, a certain amount of the admixtures added to the tungsten oxide enters the tungsten lattice forming a solid solution while a certain portion remains undissolved and undergoes elongation during the plastic reworking along the tungsten fibers. Heat treatment of the filaments may promote - to a certain extent - a transfer of part of the undissolved foreign phases into the solution as well as a more uniform distribution of these phases in the lattice of the base material. At a suitably long

TABLE 1

LIST OF HEAT-TREATMENT VARIANTS FOR TESTING THE SUITABILITY OF THE TECHNOLOGY OF VARIOUS FIRMS FOR FILAMENTS MADE OF GK ZML WIRE

Test No.	Firm	Core	Anneal I Temperature, °C	Anneal II		
				Duration (min)	Temperature, °C	Atmosphere
40	ZWLE	Mo	1100	10	1200	moist hydrogen
46	ZWLE	Fe	1100	10	1200	moist hydrogen
41	Lumalampan	Fe	1100	10 5	1200 to 1400	moist hydrogen dry hydrogen
42	Lumalampan	Mo	1100	5	1200 to 1400	dry hydrogen
43	Philips	Fe	900	15	1100	moist hydrogen
44	Philips	Mo	900	15	1100	moist hydrogen
45	Berliner Glühlampenwerk	Mo	1150 to 1400	5	1400	moist hydrogen

duration and a suitably high temperature of the anneal II, the extensive promotion of primary recrystallization may be accompanied by the formation of secondary recrystallization centers. The anneal I probably contributes only to some stress relief of the wire, perhaps causing only a negligible degree of primary recrystallization. The process is of too short a duration to promote a more uniform redistribution of the admixtures or a formation of secondary recrystallization nuclei.

In the anneal II of too short a duration (at 1200°C), the foreign phases have no time to enter into solution, nor can a proper redistribution of the impurity atoms in the solution take place. The undissolved foreign phases may hasten recrystallization at some sites, while at other sites excessively large

TABLE 2

AVERAGE LENGTH OF CRYSTALS IN RECRYSTALLIZED FILAMENTS OF GK ZML WIRE, HEAT-TREATED ACCORDING TO THE TECHNOLOGY OF VARIOUS FIRMS

Test No.	Number of Crystals in Filament	Average Length of Crystals (Crystals per Turn)
40	428	3.9
46	433	3.8
41	407	4.1
42	400	4.15
43	594	2.8
45	311	5.3

concentrations of dissolved atoms will hamper the recrystallization by excessive blocking of the dislocations, and at still others the insufficient amount of undissolved phases will increase the tendency of the grain boundaries to straighten and to become oriented perpendicular to the wire axis. The irregularly proceeding recrystallization may bring about a concentration of internal strain, which may be the cause of warping of the filaments.

With an increase in the anneal II period, there occurs an increase in the number of impurity atoms entering the tungsten-based solid solution as well as a greater uniformity of distribution of the original atoms in the solution; this leads to a more uniform course of the recrystallization and to an increase in grain size after burning. The recrystallization after anneal II at too low a temperature (10 min in time) proceeds in the same manner as at too short a period. On the other hand, at excessively high anneal II temperatures, a situation might occur in which, at insufficient stress relief of the material and nonuniform distribution of the admixtures, secondary recrystallization nuclei may form already during the anneal II, with the secondary recrystallization proceeding irregularly during the burning. Excessively rapid breakdown of the effects of strengthening the material by cold-working may also lead to warping of the filaments. The recrystallization during the burning proceeds rapidly but not uniformly. The curve for the anneal II temperature vs. grain size shows a grain-size optimum (ratio of G to N). At too low a temperature, the lack of stress relief leads to an excessive number of centers in the course of later burning, while too high a temperature results in the immediate formation of a large number of centers during the anneal II. In the two-step anneal II, a favorable distribution of the impurity atoms in the solution and stress relief of the material occur during the first step, preventing warping of the filaments. During the second step primary recrystallization takes place, and secondary recrystallization nuclei will form uniformly. Recrystallization during burning proceeds rapidly and the small quantity of foreign phases contributes to the increase in grain size.

If the anneal II is omitted, the lack of stress relief of the filaments causes considerable warping, and the nonuniform recrystallization results in extensive susceptibility to sagging. As a consequence of the incomplete primary recrystallization and the lack of secondary recrystallization centers during heat treatment, primary recrystallization will take place during the burning, and its irregularity will contribute to increased primary sagging.

The effect of the anneal I temperature, in view on the possibility of reaction of the graphite coating of the wire at high temperatures, is more complex. At high anneal I temperatures (above 1200°C) a sufficient stress relief of the filaments takes place; however, the carbon from the graphite coating of the wire reacts in this case with the tungsten to form carbides, causing nonuniform heating of the filament and setting up high internal strain at nonuniform recrystallization, as a result of the nonuniform temperature distribution and of the presence of additional phases. This contributes to increased warping and sagging and to a tendency of burn-out of the filaments during operation. At too low an anneal I temperature, the removal of the graphite from the surface of the wire may be incomplete, with a possible harmful reaction during the subsequent high-temperature anneal II and insufficient stress relief of the filaments. Thus, low anneal I temperatures lead to the same results as excessively high ones. With the use of two-step anneal I, the filaments undergo maximum /65 stress relief prior to onset of the recrystallization. The gradual elimination of stresses prior to recrystallization (the annealing time is too short for recrystallization to take place) facilitates the optimum distribution of the impurity atoms in the tungsten. As a consequence of the satisfactory stress relief of the wire and the uniform distribution of the dissolved impurity atoms, the incubation period of the primary and secondary recrystallization is long so that no primary recrystallization takes place during the anneal II and the entire process of recrystallization during burn occurs at a considerable lag. The uniform distribution of the impurity atoms in the solid solution ensures a rapid course of the already-started primary and secondary recrystallization. Both the course of the recrystallization process and the character of the final structure approach the ideal, creating a tendency in the grain boundaries toward straight lines and perpendicularity to the wire axis. Such a course of recrystallization ensures excellent resistance of the filaments to warping and primary sagging after burning on the automatic mounting machine, but increases the susceptibility to final sagging (after protracted operation of the bulb).

CONCLUSIONS

Several tests were performed with the purpose of determining the optimum parameters for the heat treatment of filaments for production-series bulbs (25, 40, 60, and 100 w/220 v) in order to obtain filaments with minimum sagging and warping and high resistance to embrittlement following heat treatment. The investigations were carried out on GK grade wire produced by the Zaklady Materiałów Lampowych in Warsaw.

Investigated: effect of duration, temperature, and procedure of anneal II. Effect of temperature and procedure of anneal I. Suitability of filament heat treatment techniques used in other countries, for GK ZML wire.

Findings: Too short an anneal II period (below 10 min) at a temperature of 1200°C increases the susceptibility of the filaments to sagging and warping. Filaments with optimum resistance to deformation at the operating temperatures are obtained with the anneal II of 20 min and longer (at 1200°C).

Both too low (below 1000°C for 10 min) as well as too high (above 1400°C) anneal II temperatures increase the tendency of filaments to sagging and warping. Best results are obtained with the use of the two-step anneal II, with the first step taking place at a temperature of about 1100°C and the second, at 1400°C.

However, too low (below 1000°C) as well as too high (above 1200°C) anneal I temperatures cause dimensional instability of the filaments in the bulb and a shortening of their lifetime. A two-step anneal I (first step at 1100°C and second step at about 1400°C) yields filaments with maximum resistance to warping and primary sagging but with lowered resistance to final sagging.

Of the heat-treatment processes used by foreign firms for production-series filaments, best results with GK ZML wire are obtained with the process used by the Lumalampan, followed in order by those of the ZWLE, BGW, and Philips. On the basis of metallographic studies, it was determined that increased susceptibility to sagging and warping is due to a disturbed (nonuniform) and possibly retarded course of the recrystallization process and to fine-grain structure. It may be assumed that, at optimum selection of the heat-treatment parameters, one can obtain a suitable distribution of the admixtures in the wire and proper stress relief of the filaments, ensuring a uniform course of crystallization and a G/N ratio (G = rate of grain coarsening, N = rate of nuclei formation) that yields crystals of maximum length. At excessively high anneal I temperatures allowance must also be made for the reaction of the carbon with the graphite coating of the wire to form tungsten carbide, which interferes with the course of crystallization both due to a change in resistance and formation of additional phases in the material.

BIBLIOGRAPHY

1. Ulmishek, L.G.: Manufacture of Electric Incandescent Lamps (Proizvodstvo elektricheskikh lamp nakalivaniya). Moscow, 1958.

2. Davis, G.L.: Recrystallization of Tungsten Wires. Metallurgia, No.10, p.117, 1958.

3. Millner, T.: Scientific Principles of the Production of Metallic Tungsten for Vacuum Technique and Influence on its Properties (Über die naturwissenschaftlichen Grundlagen der Erzeugung von metallischem Wolfram für die Vakuumtechnik und die Beeinflussung seiner Eigenschaften). Acta Tech.

Acad. Sci. Hung., No.17, p.67, 1957.

4. Meijering, J.L. and Rieck, G.D.: The Function of Additives in Tungsten for Filaments. Philips Tech. Rev., No.4, p.109, 1957/58.
5. Millner, T., Prohaška, J., and Horwath, A.: Influence of Traces of Foreign Substances on the Secondary Recrystallization of Tungsten Wires (Der Einfluss von Fremdsubstanzspuren auf die sekundäre Rekristallisation von Wolframdrähten). Acta Tech. Acad. Sci. Hung., No.17, p.289, 1957.
6. Thompson, B.: Embrittlement of Tungsten Wires. Nature, No.8, p.360, 1955.
7. Mannerkoski, M.: Recrystallization of "Doped" Tungsten Wires. J. Inst. Metals, Vol.88, p.397, 1959/60.
8. Swalin, R.A. and Geisler, A.H.: The Recrystallization Process in Tungsten as Influenced by Impurities. J. Inst. Metals, Vol.86, p.119, 1957/58.
9. Jesionek, B. and Kostkowski, A.: Causes of Peeling of Tungsten Wires (Przyczyny luszczenia się drutów wolframowych). Rudy Metale Nieżelazne, No.1, p.23, 1964.
10. Semenov, M.I.: Manufacture of Hot Cathodes for Electric Vacuum Devices (Proizvodstvo podogrevateley katodov elektrovakuumnykh priborov). Moscow, 1962.

Translated for the National Aeronautics and Space Administration by the O.W.Leibiger Research Laboratories, Inc.